



Advanced Exploration Systems Program

Large-Scale Spacecraft Fire Safety Experiments in ISS Resupply Vehicles

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Nov 7, 2013

29th American Society for Gravitational and Space Research
Orlando, Florida, USA, November 3 – 8, 2013

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Outline



- ◆ **Overview of the Spacecraft Fire Safety Demonstration Project**
- ◆ **Science and Technology Demonstration Objectives**
 - Details of Sample Selection
- ◆ **Supporting Ground-based Research**



Spacecraft Fire Safety Demonstration *Requirements and Goals*



◆ Level 1 Requirements

- The project shall conduct an experiment on an International Space Station resupply vehicle after it leaves the ISS and before it re-enters the Earth's atmosphere.
- The experiment performed on this vehicle shall meet a critical need for developing rational spacecraft fire safety strategy on future exploration vehicles.

◆ Project Goals

- Conduct a spacecraft fire safety experiment on three flights of Orbital Science's Cygnus vehicle that investigates large-scale flame spread and material flammability limits in long duration low-gravity.
 - Orb-5: February 2015 **probable slip to December 2015**
 - Orb-6: September 2015 **probable slip to June 2016**
 - Orb-7: February 2016 **probable slip to October 2016**
- Complete the major experiment development work no later than September 30, 2014.

◆ Needs:

- ◆ Quantify the development and growth of a realistic fire for exploration vehicles
- ◆ Determine low-g flammability limits for spacecraft materials



Saffire Overview



Objectives:

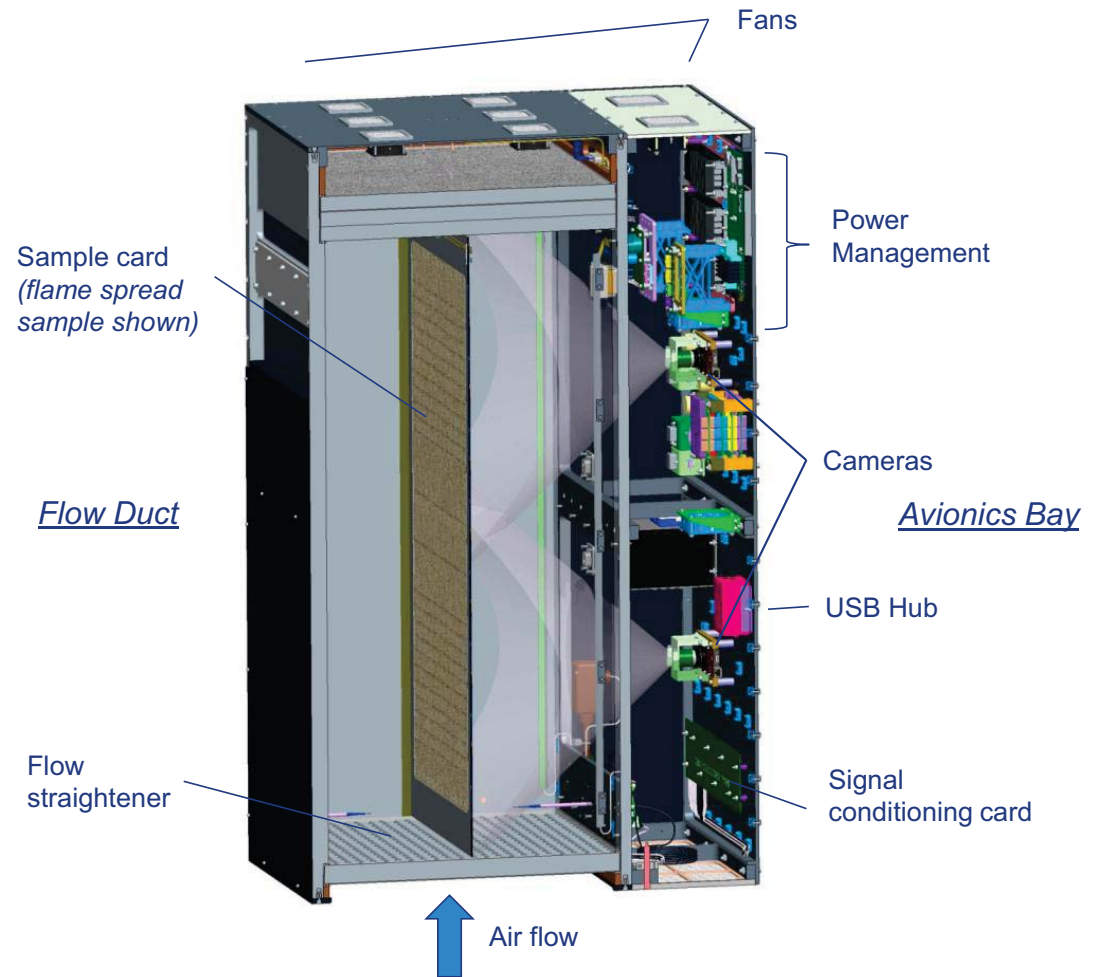
- ◆ *Saffire-I*: Assess flame spread of large-scale microgravity fire
- ◆ *Saffire-II*: Verify oxygen flammability limits in low gravity
- ◆ *Saffire-III*: Similar to *Saffire-I* at different air flow

Data:

- ◆ Flame size, position, and spread rate (video)
- ◆ Flame intensity (radiometer)
- ◆ Flame stand-off distance (t/c)
- ◆ Flame/plume temperature (t/c)
- ◆ O₂, CO₂ concentrations

- *Data obtained from the experiment will be used to validate modeling of spacecraft fire response scenarios*
- *Evaluate NASA's normal-gravity material flammability screening test for low-gravity conditions.*

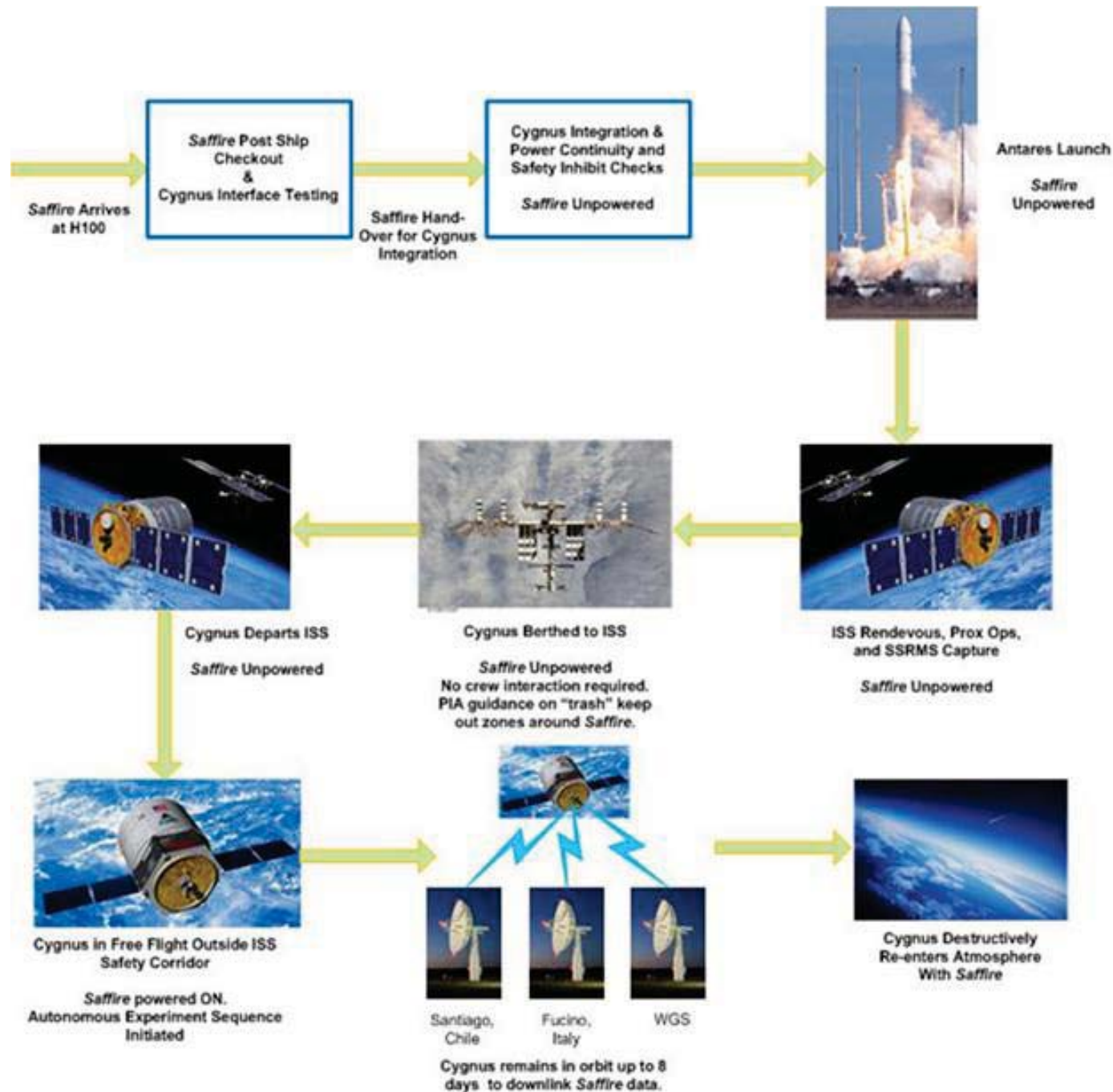
Experiment Layout



. Dimensions are approximately 53- by 90- by 133-cm

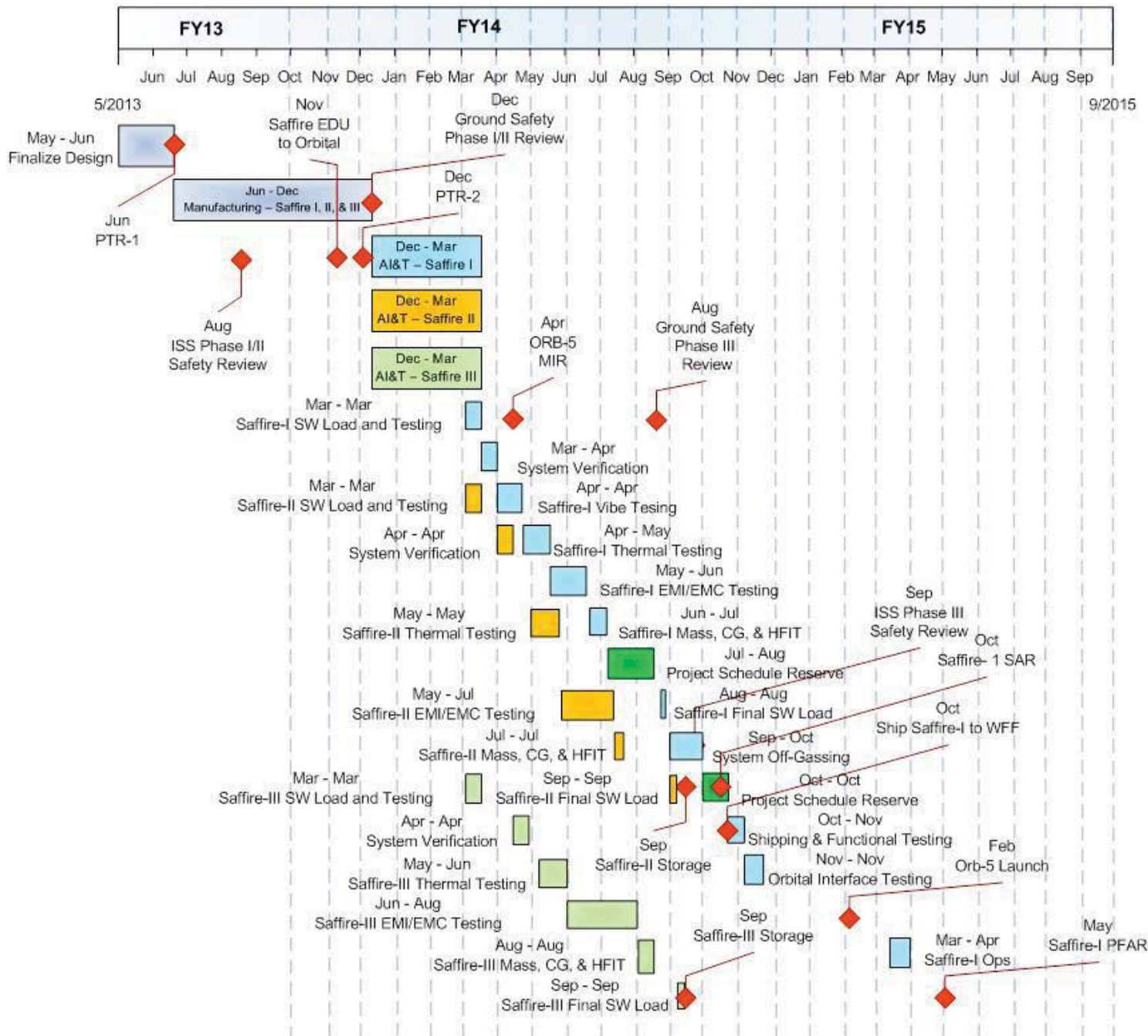


Operations Concept





Saffire-I, II, & III Schedule & Milestones



Milestone	Date
PTR-1	6/19/13
FSDP Submit	7/3/13
ISS Flight Safety Phase I/II Review	8/20/13
Saffire Simulator to Orbital	11/2013
PTR-2	12/4/13
System AI&T Start	12/12/13
Ground Safety Phase I/II Review	12/12/13
Verification and Environmental Test Start	3/19/14
Ground Safety Phase III Review	8/21/14
ISS Phase III Review	9/24/14
SAR	10/17/14
Saffire-I Ship to WFF	10/24/14



Spacecraft Fire Safety Demonstration Research Objectives



◆ Two major stakeholders in sample selection

- Scientific community
 - Address both the “no ignition” and “no flame spread” criteria involved in passing standard material flammability testing
 - Materials can pass NASA-STD-6001 Test 1 because ignition energy is not sufficient to start the flame spread process
- NASA Materials and Processes
 - If a material passes NASA Test 1 on the ground, will it pass the test in microgravity? (i.e. is the ground test the worst case scenario)

➤ The long-term relevance to spacecraft fire safety applications depends on the careful and well-informed selection of the sample materials

- Relevance requires:
 - Scalability
 - Amenable to modeling



Sample Selection Constraints

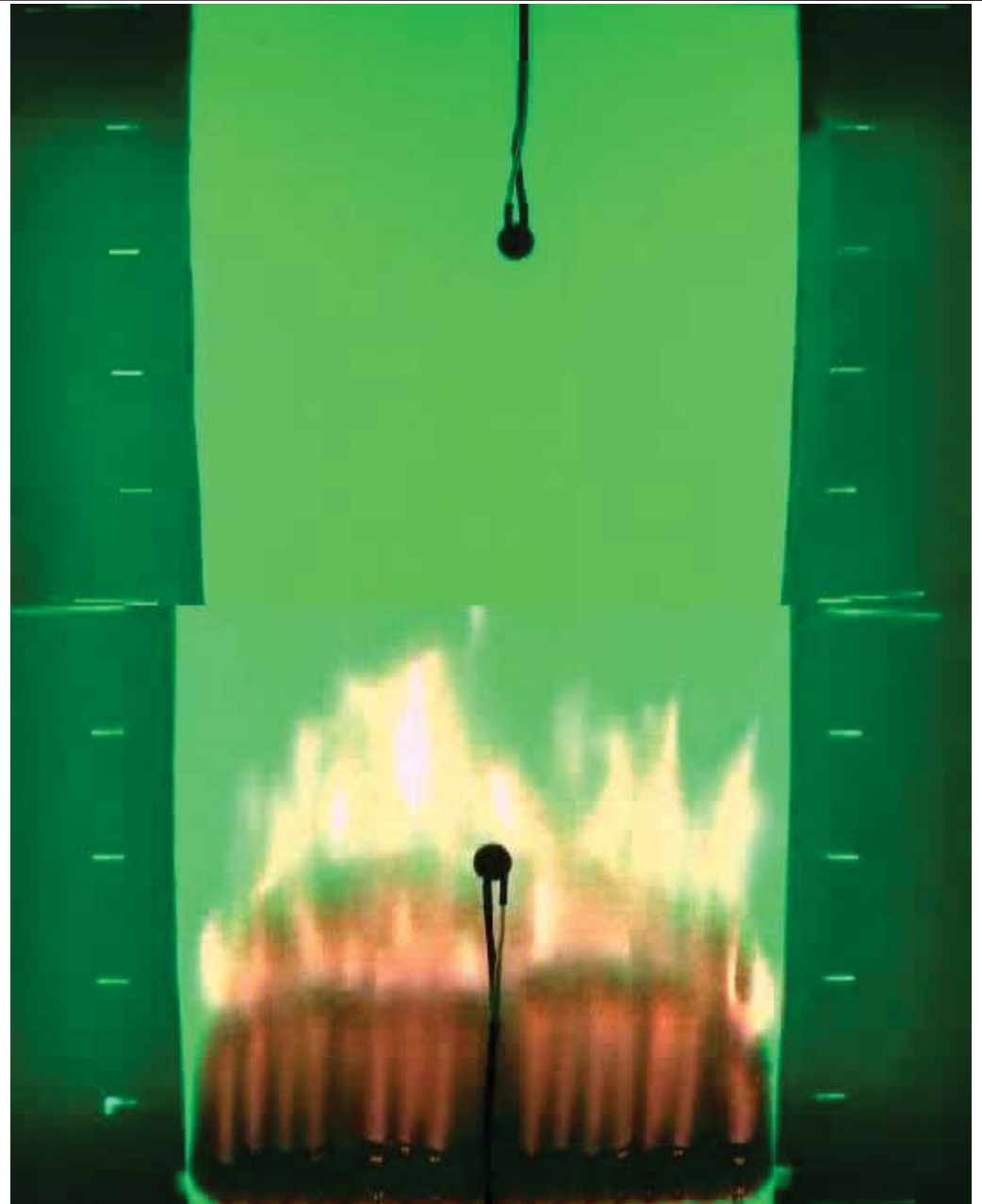


- Dimensions and energy release
 - 1 or 2 flame spread (large) samples (0.5 m x 1.0 m)
 - 9 or 18 material flammability samples (5 cm x 30 cm)
 - Thickness can be a maximum of 10mm
 - Total energy released can be a maximum of 54 grams of fuel (cellulose equivalent)
- Data Acquisition
 - Thermocouples (6 total shared by all 9 samples)
 - Radiometer (two sides)
 - Camera (front view)
 - Maximum run time of 6 minutes
- Flow
 - Flow rate range is 10-30 cm/s
 - Concurrent or opposed
- Ignition power and system
- Long-term sample storage

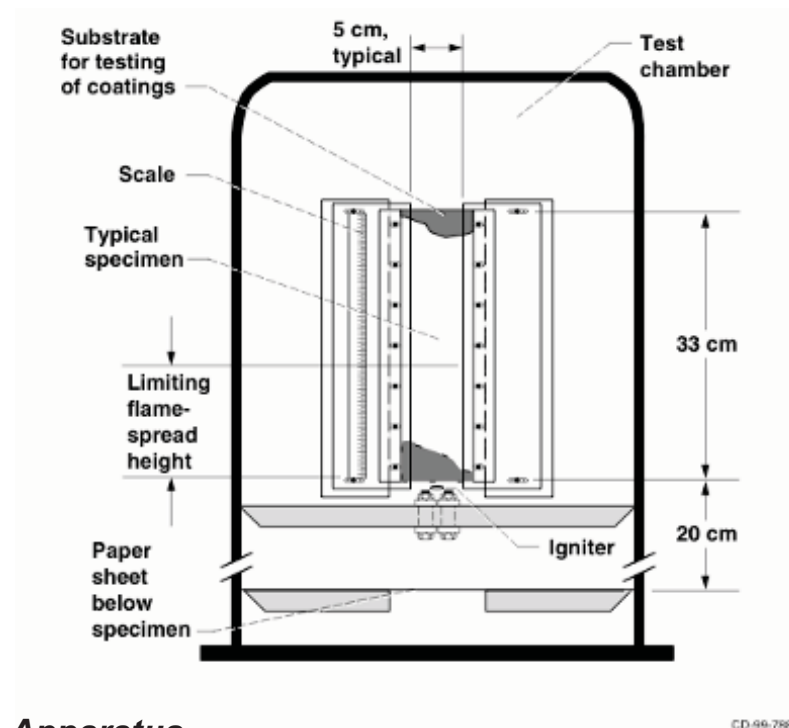
Large-Scale Flame Spread Test

- Upward flame spread test on a fabric sample
 - Solid Inflammability Boundary at Low Speed (SIBAL)
 - Cotton on a fiberglass substrate
 - 75% cotton by weight (18.05 mg/cm^2)
 - 0.4 m x 0.94 m
 - Saffire-I: 20 cm/s air flow
 - Saffire-III: 30 cm/s air flow

Normal gravity test conducted in the VF-13 facility at NASA GRC.



- NASA-STD-6001 describes the test methods used to qualify materials for use in space vehicles.
- The primary test to assess material flammability is Test 1: Upward Flame Propagation
- Materials “pass” this test if the flame self-extinguishes before it propagates 15 cm
- *Maximum oxygen concentration (MOC) is defined as the highest O_2 at which material passes Test 1*



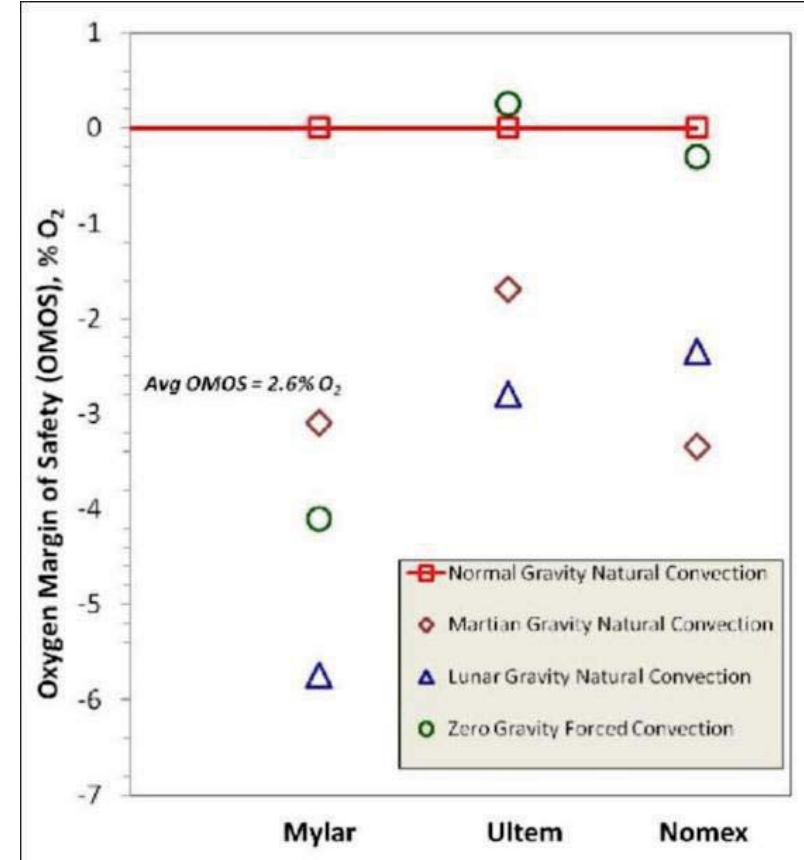
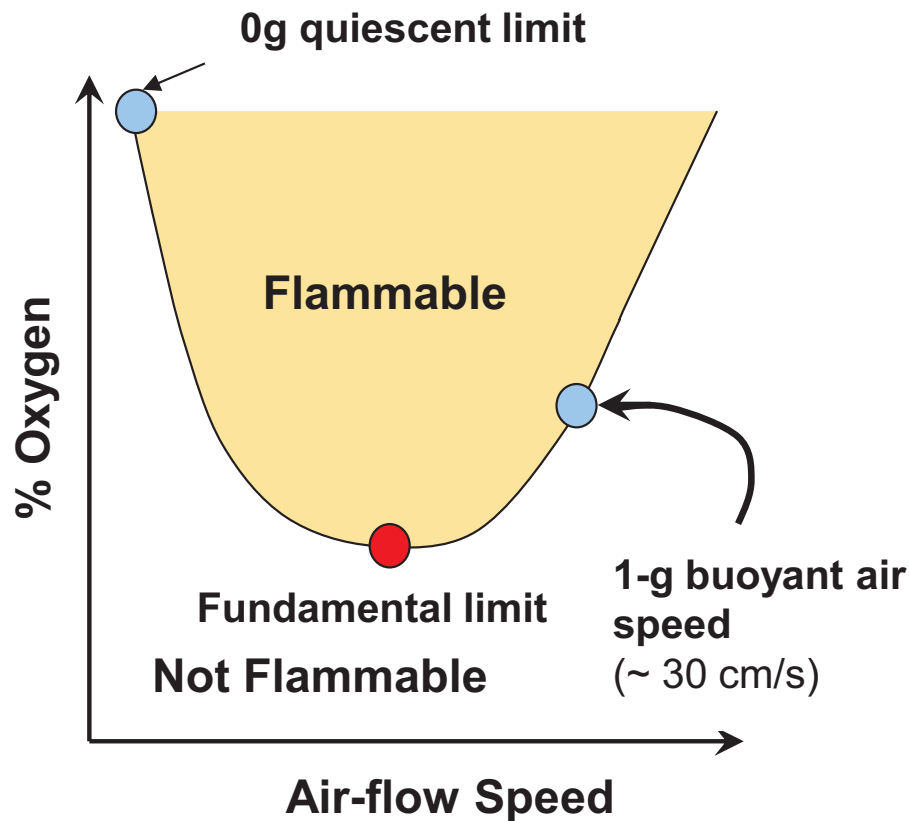
Test 1 Apparatus



Low-g Maximum Oxygen Concentration



- Flammability limits determined by this test are strongly influenced by natural convection
 - Normal gravity flames induce a natural convective flow that transports oxygen to the flame *but also removes heat*
 - Forced convection in low-g transports oxygen to the flame but rate of heat removal is reduced



◆ Build data sets on scalability of low-g fires

- Materials that have been tested in low-g at different length scales

◆ Amenable to modeling

- Large, vehicle scale fire modeling
 - Impact on vehicle
 - Real-time modeling of fire response
- Details of low-g flame spread

◆ Conclusive low-g flammability limit (Maximum Oxygen Concentration) data

- Flammability limit sample materials must cross the flammability limit in 21% O_2
 - Requires approaches to alter flammability including: material thickness, heat loss (metal backing/matrix), radiative feedback (surface variation (grooves), inert (non-flammable) coatings

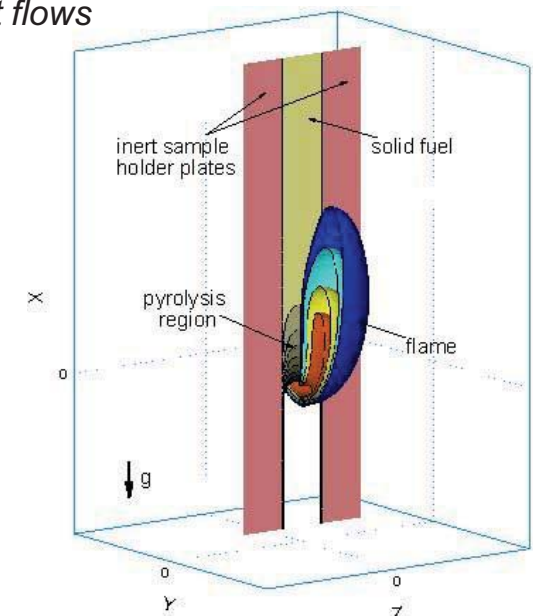


Burning and Suppression of Solids (BASS)

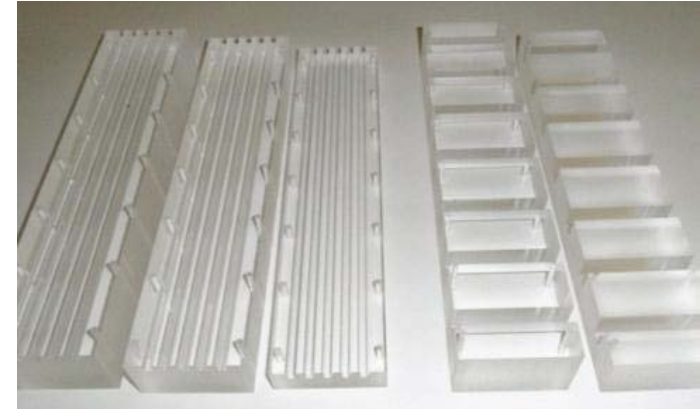
2cm and 1cm Flat Samples

- SIBAL- cotton-fiberglass fabric
- Nomex- flame resistant material related to nylon
- Ultem - thermoplastic resins used in medical and chemical instrumentation

Three-dimensional, time dependent upward flame spread in buoyant flows



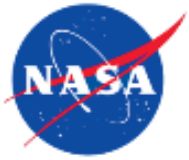
- ◆ **Nomex (HT90-40, Combo)**
- ◆ **Mylar**
- ◆ **Ultem**
- ◆ **SIBAL cloth**
 - Solid Inflammability Boundary at Low Speed (SIBAL)
 - *Cotton on a fiberglass substrate*
 - *75% cotton by weight (18.05 mg/cm²)*
- ◆ **Silicone (2-3 thicknesses, concurrent/opposed spread)**
- ◆ **PMMA**
 - Straight, tapered, or structured
- ◆ **Cellulose (with backing/metal matrix)**
- ◆ **Fire-resistant coating**
- ◆ **Wires**



PMMA-samples shaped at University of Bremen with grooves parallel or perpendicular to the flame propagation direction



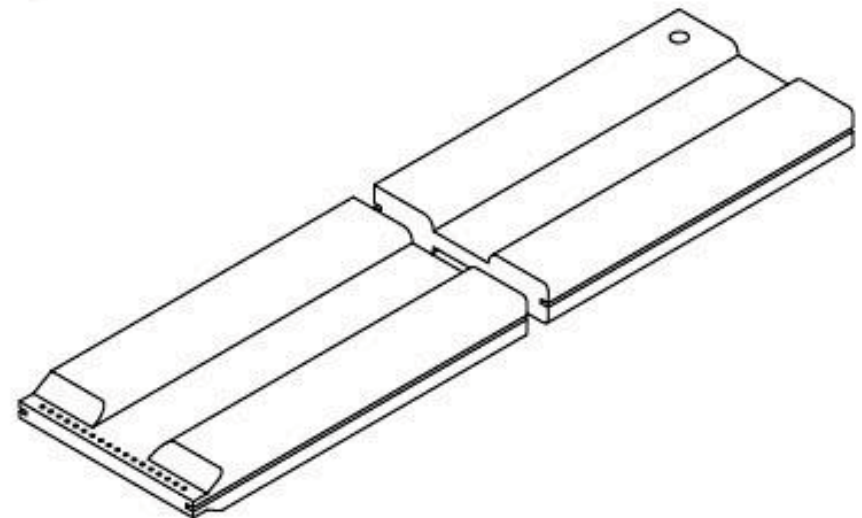
MOC and ULOI of Potential *Saffire* Samples



	MOC	ULOI
Composites and Laminates		
Epoxy/Glass laminate NEMA G-11, H-23842	23	23.6
Rigid Plastics		
P1700 polysulfone	25	27.5
Zytel 42 from 93-27463	24.1	24.5
Fabrics		
Nomex HT 90-40, L/N 7254	24	24.8
Nylon Tricot ST11N791-01	23	24.3
TCU Bottom, P/N SKD38114488-01	21	22.8
Nomex Webbing P/N 9981	22	23.4
Foams		
L-200 Minicel Foam	20	21.7
TA-301 Polyimide foam	25	27.3
Films		
Ultem 1000 Film, P/N DLI1648	21	22.1
PEEK Victrex Film, 10-mil	21.1	22
Kapton HN Film	26	27.2
SSP-M823 Silicone membrane, 0.004"	17	17.5
SSP-M823 Silicone membrane, 0.010"	18	19.7
SSP-M823 Silicone membrane, 0.014"	19	21
SSP-M823 Silicone membrane, 0.024"	20	22.8
SSP-M823 Silicone membrane, 0.040"	22	23.4

Selected Samples

- ◆ Nomex (HT90-40) with PMMA promoter (1 sample)
- ◆ SIBAL cloth (2 samples at the same flow rates as Saffire 1 & 3)
- ◆ Silicone (3 thicknesses for concurrent spread and 1 thickness for opposed spread)
- ◆ **PMMA** 10 mm thick
 - Flat sample
 - Structured sample



Top view of PMMA sample -edges have different radii

- ♦ Example with 4 inch SIBAL cloth promoter
- ♦ 8 inch Nomex



After Test



After Igniter is off



Flame Out



Downward Silicone



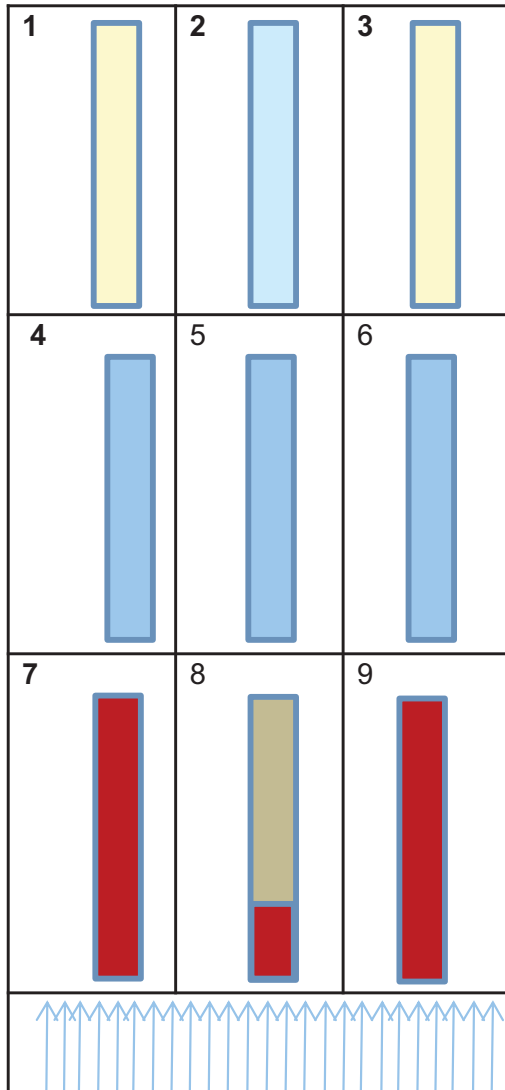
- ♦ Average ~ 5 minutes to burn 30 cm
- ♦ 0.014" thick Silicone will burn downward but not upward








.01" down burn



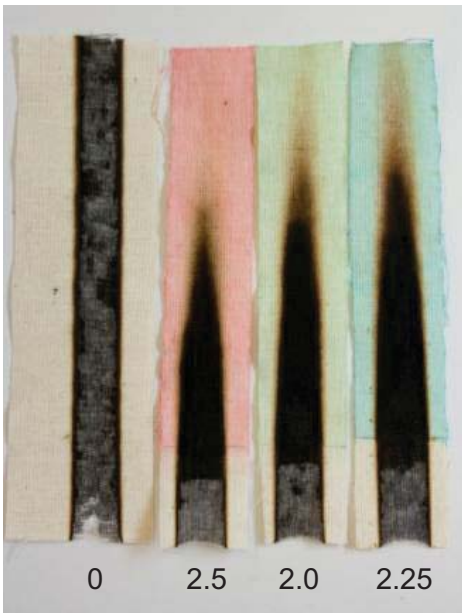
Flight 2 Sample Selection



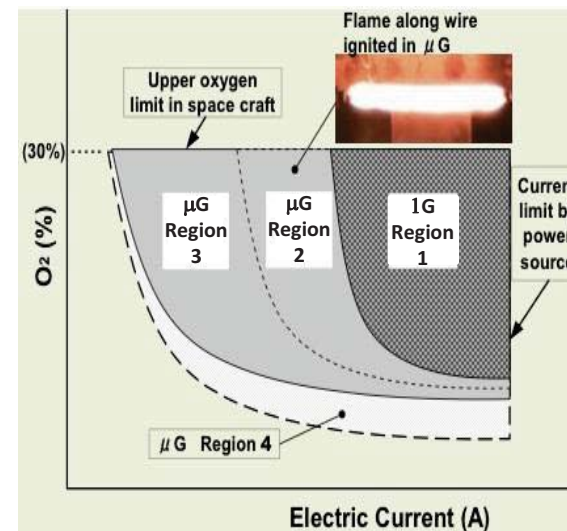
Sample #	Material	Sample Thickness	Flow (cm/s)	Igniter Position
Saffire-2-S1	SIBAL	N/A	20	Bottom
Saffire-2-S2	Silicone down	0.36 mm (0.014") Silicone	20	Top
Saffire-2-S3	SIBAL	N/A	30	Bottom
Saffire-2-S4	Flam limit 1 Silicone	0.25 mm (0.010") Silicone	20	Bottom
Saffire-2-S5	Flam limit 2 Silicone	0.36 mm (0.014") Silicone	20	Bottom
Saffire-2-S6	Flam limit 3 Silicone	0.61 mm (0.024") Silicone	20	Bottom
Saffire-2-S7	PMMA 2 sided burning	10 mm with tapered edge for ignition	20	Bottom
Saffire-2-S8	Transition 1: PMMA to NOMEX	N/A	20	Bottom
Saffire-2-S9	PMMA 2 sided burning	10 mm with tapered edge for ignition	30	Bottom

Pmma  Silicon  Nomex 
 Sibal  Silicone opposed 

- ♦ The outcomes of this experiment are multiplied by tasks performed by contributing team members (and the funding from other organizations)
 - Sample Selection
 - Structured materials:
 - Nickolay Smirnov, *Moscow Lomonosov State University, Moscow, Russia*
 - Christian Eigenbrod, *University of Bremen (ZARM), Bremen, Germany*
 - Wires: Osamu Fujita, *Hokkaido University, Sapporo, Japan*
 - Coated materials: James S. T'ien, *Case Western Reserve University, Cleveland, OH, USA*
 - Nomex: Carlos Fernandez-Pello, *UC Berkeley, Berkeley, CA, USA*



Guanylurea Phosphate (GUP) (g) in 25 mL water (samples are 2 cm x 18 cm)



Ignition map of overloaded wire. Region 1: Ignition limit in 1-g. Region 2: Ignition limit in short-term μ g tests. Region 3: Ignition limit in long-term μ g tests. Region 4: Ignition but no sustained flame.

◆ The outcomes of this experiment are multiplied by tasks performed by contributing team members (and the funding from other organizations)

- *Modeling*

- Low-g Fire Dynamics

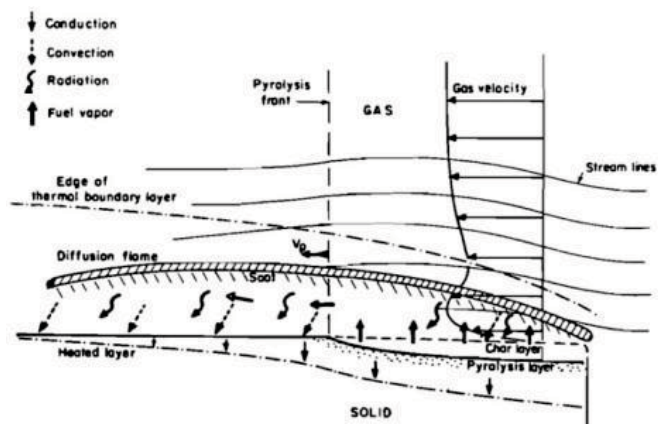
- James S. T'ien , *Case Western Reserve University, Cleveland, OH, USA*

- Real-time fire response:

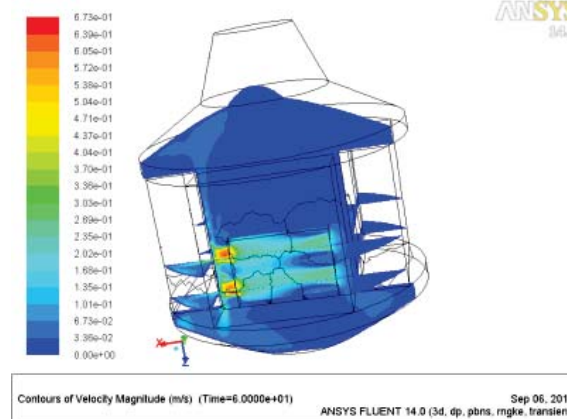
- Jose L. Torero, *University of Queensland, Brisbane, Australia*
- Adam J. Cowlard, *University of Edinburgh, Edinburgh, UK*

- Vehicle-scale fire scenario modeling

- Sebastien Rouvreau, *Belisama R&D, Toulouse, France*
- Dan Dietrich, *NASA GRC, Cleveland, OH*
- Suleyman Gokoglu, *NASA GRC, Cleveland, OH*

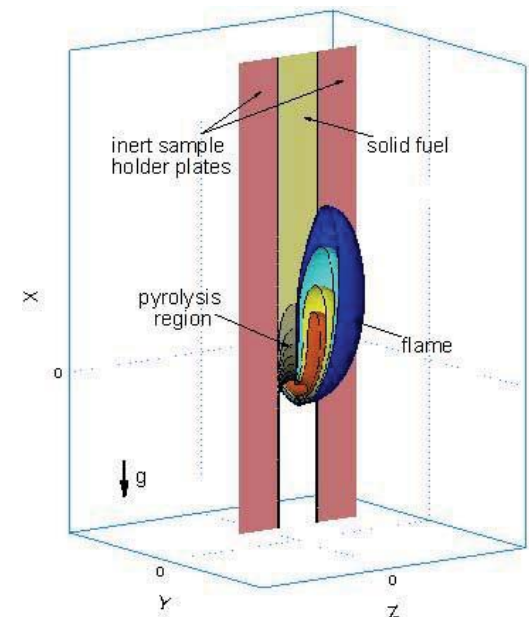


Schematic for a concurrent spread over the flat surface of a solid combustible



: Fluent model calculation of velocity magnitude in ATV configuration after 1 minute of heat release.

Three-dimensional, time dependent upward flame spread in buoyant flows





Ground-based Supporting Research (continued)



- ♦ **The outcomes of this experiment are multiplied by tasks performed by contributing team members (and the funding from other organizations)**
 - *Diagnostics*
 - Fuel Characteristics: Adam J. Cowlard, *University of Edinburgh, Edinburgh, UK*
 - *Flame Propagation Apparatus: Heat release rate of materials to support detailed modeling of fire response*
 - Soot Volume Fraction in Low-g: Guillaume Legros, *Université Pierre et Marie Curie, Paris, France*
 - *Laser extinction technique to measure soot volume fraction in large-scale normal- and low-g flames*



Summary



- **The *Saffire* experiment (Spacecraft Fire Safety Demonstration Project) is in development to address knowledge gaps in low-g material flammability**
- **Sample were selected to meet stakeholder requirements and to ensure the long-term impact of the project on the spacecraft fire safety protocol.**
- **Samples will address both flame spread and material flammability understanding.**
- **Recent studies and analyses have confirmed the fire safety needs for long-term exploration missions. Spacecraft fire safety technologies have been identified as enabling for some exploration missions, enhancing for others**
 - The *Saffire* experiments address several of these but lack fire detection, suppression, and post-fire cleanup
- **An end-to-end demonstration of a fire detection, suppression, and clean-up scenario would verify hardware and the ability to properly size fire response hardware**

